Search for CP violation in the decay D±→KS0 ±

BABAR Collaboration ; del Amo Sanchez, P ; Snoek, H L ; et al

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Search for *CP* Violation in the Decay $D^{\pm} \rightarrow K_S^0 \pi^{\pm}$

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We report on a search for *CP* violation in the decay $D^{\pm} \to K^0_S \pi^{\pm}$ using a data set corresponding to an integrated luminosity of 469 fb^{-1} collected with the *BABAR* detector at the PEP-II asymmetric energy e^+e^- storage rings. The *CP*-violating decay rate asymmetry A_{CP} is determined to be $(-0.44 \pm 0.13(\text{stat}) \pm 0.10(\text{syst}))\%$, consistent with predictions based on the standard model. This is currently the most precise measurement of this parameter.

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In the standard model (SM), *CP* violation (CPV) arises from the complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Measurements of the CPV asymmetries in the K and B meson systems are consistent with expectations based on the SM and, together with theoretical inputs, lead to the determination of the parameters of the CKM matrix. CPV has not yet been observed in the charm sector, where the theoretical predictions based on the SM for CPV asymmetries are at the level of 10^{-3} or below [2].

In this Letter we present a search for CPV in the decay $D^{\pm} \to K^0_S \pi^{\pm}$ by measuring the CPV parameter A_{CP} defined as:

$$A_{CP} = \frac{\Gamma(D^+ \to K^0_S \pi^+) - \Gamma(D^- \to K^0_S \pi^-)}{\Gamma(D^+ \to K^0_S \pi^+) + \Gamma(D^- \to K^0_S \pi^-)}, \quad (1)$$

where Γ is the partial decay width for this decay. In the decay $D^{\pm} \to K^0_S \pi^{\pm}$, considering only the CPV in $K^0 - \overline{K}^0$ mixing, the predicted value for A_{CP} is $(-0.332 \pm 0.006)\,\%$ [3] and contributions from non-SM processes may reduce the value of A_{CP} or enhance it up to the level of one percent [4, 5], therefore a significant deviation of the A_{CP} measurement from the expectation would be evidence for the presence of new physics beyond the SM. Due to the smallness of the predicted value, this measurement requires a large data sample and precise control of the systematic uncertainties. The Belle collaboration has recently reported a measurement of $A_{CP} = (-0.71 \pm 0.19(\text{stat}) \pm 0.20(\text{syst}))\%$ [6].

The data used in this analysis were recorded at or near the $\Upsilon(4S)$ resonance by the *BABAR* detector at the PEP-II storage rings. The *BABAR* detector is described in detail elsewhere [7]. The data sample corresponds to an integrated luminosity of 469 fb^{-1}. To avoid any bias from adapting the analysis procedure to the data, we perform a "blind" analysis where all aspects of the analysis, including the statistical and systematic uncertainties, are validated with data and Monte Carlo (MC) simulation based on GEANT4 [9] before looking at the value of A_{CP}. The coordinate system defined in [7] is assumed throughout the Letter.

We select $D^\pm \to K^0_S\pi^\pm$ decays by combining a K^0_S candidate reconstructed in the decay mode $K^0_S \to \pi^+\pi^-$ with a charged pion candidate. A K^0_S candidate is reconstructed from two oppositely charged tracks with an invariant mass within ± 10 MeV/c^2 of the nominal K^0_S mass [3], which is equivalent to slightly more than $\pm 2.5\,\sigma$ in the measured K^0_S mass resolution. The χ^2 probability of the $\pi^+\pi^-$ vertex fit must be greater than 0.1 %. To reduce combinatorial background, we require the measured flight length of the K^0_S candidate to be greater than 3 times its uncertainty. A reconstructed charged track that has $p_T \geq 400$ MeV/c is selected as a pion candidate, where p_T is the magnitude of the momentum in the plane perpendicular to the z axis. The pion candidate is also required not to be identified as a kaon, a proton, or an electron, as determined by the Cherenkov angle and number of photons measured by the internally reflecting ring-imaging Cherenkov detector, the ionization energy loss measured by the charged-particle tracking system, and the energy deposited in the electromagnetic calorimeter [7]. These selection criteria for the pion candidate are very effective in reducing the charge asymmetry from track reconstruction and identification, as inferred from studying the large control sample described later. A kinematic fit to the parameters of the whole decay tree is then performed with no additional constraints [8]. We retain only $D^\pm$ candidates having a χ^2 probability for this fit greater than 0.1% and an invariant mass $m(K^0_S\pi^\pm)$ within $\pm 65\,\text{MeV}/c^2$ of the nominal D^+ mass [3], which is equivalent to more than $\pm 8\,\sigma$ in the measured $D^\pm$ mass resolution. Motivated by Monte Carlo simulation studies, we further require the magnitude of the $D^\pm$ candidate momentum in the e^+e^- center-of-mass (CM) system, $p^*(D^\pm)$, to be between 2 and 5 GeV/c. This criterion reduces the combinatorial background to an acceptable level, but also keeps some $D^\pm$ mesons from B mesons decays (they are $\approx 8\%$ of the selected sample). Additional background rejection is obtained by requiring that the impact parameter of the $D^\pm$ candidate with respect to the beam-spot, projected onto the plane perpendicular to the z axis, be less than 0.3 cm and the $D^\pm$ lifetime $\tau_{xy}(D^\pm)$ be between -12.5 and 31.3 ps. The lifetime is measured using $L_{xy}(D^\pm)$, defined as the distance of the $D^\pm$ decay vertex from the beam-spot projected onto the plane perpendicular to the z axis.

To further improve the search sensitivity, a Boosted Decision Tree (BDT) algorithm [10] is constructed from seven discriminating variables for each $D^\pm$ candidate: $\tau_{xy}(D^\pm)$, $L_{xy}(D^\pm)$, the CM momentum magnitude $p^*(D^\pm)$, the momentum magnitudes and transverse components with respect to the beam axis for both the K^0_S and pion candidates. The final selection criteria are based on the BDT output and optimized using truth-matched signal and background candidates from the MC sample. For the optimization, we maximize the $S/\sqrt{S+B}$ ratio, where S and B are the numbers of signal and background candidates whose invariant mass is within $\pm 31\,\text{MeV}/c^2$ of the nominal $D^\pm$ mass.

A binned maximum likelihood (ML) fit to the $m(K^0_S\pi^\pm)$ distribution for the retained $D^\pm$ candidates is used to extract the signal yield. The total probability density function (PDF) is the sum of signal and background components. The signal PDF is modeled as a sum of three Gaussian functions, two of them with common mean. The background PDF is taken as a sum of two components: a background from $D^\pm_s \to K^0_S K^\pm$, where the $K^\pm$ is misidentified as $\pi^\pm$, and a combinatorial background from other sources. Based on MC studies, the yield of $D^\pm \to \pi^\pm\pi^\mp\pi^\pm$ decays in the final data sample is estimated to be 0.02% of the signal and the estimated A_{CP} for this source to be less than 0.002%. Therefore a PDF to model this component is not included in the fit. The background from the decay $D^\pm_s \to K^0_S K^\pm$ is modeled using a PDF sampled from the MC histogram for this mode. The combinatorial background is described as a second-order polynomial. The fit to the $m(K^0_S\pi^\pm)$ distribution yields $(807.4 \pm 0.1) \times 10^3$ signal events. The data and the fit are shown in Fig. 1. All of the fit parameters are extracted from the fit to the data sample apart from the normalization of the background due to $D^\pm_s \to K^0_S K^\pm$, which is fixed to the value predicted by the MC simulation.

We determine A_{CP} by measuring the signal yield asymmetry A defined as:

$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}}, \tag{2}$$

where $N_{D^+}(N_{D^-})$ is the number of fitted $D^+ \to K^0_S\pi^+ (D^- \to K^0_S\pi^-)$ decays. The quantity A is the result of two other contributions in addition to A_{CP}. There is a physics component due to the forward-backward (FB) asymmetry (A_{FB}) in $e^+e^- \to c\overline{c}$, arising from γ^*-Z^0 interference and high order QED processes in $e^+e^- \to c\overline{c}$. This asymmetry will create a difference in the number of reconstructed D^+ and D^- decays due to the FB detection asymmetries arising from the boost of the CM system relative to the laboratory frame. There

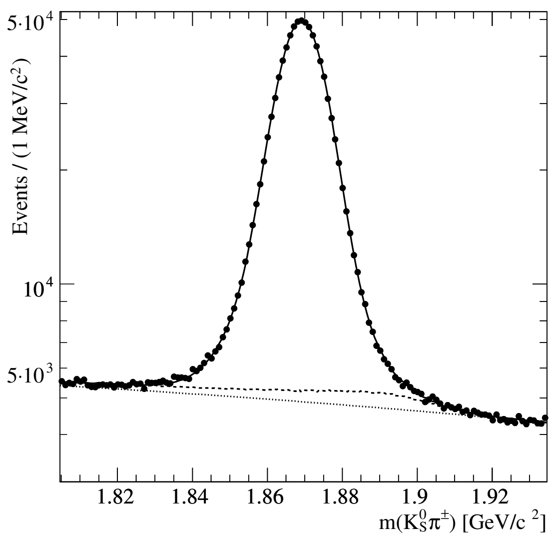

FIG. 1: Invariant mass distribution for $K_S^0\pi^\pm$ candidates in the data (black points). The solid curve shows the fit to the data. The dashed line is the sum of all backgrounds, while the dotted line is combinatorial background only. The vertical scale of the plot is logarithmic.

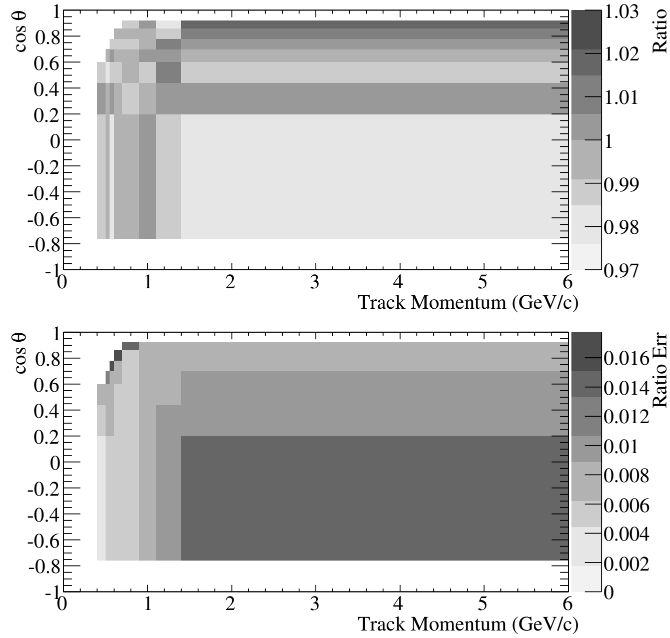

FIG. 2: Map of the ratio between detection efficiency for π^+ and π^- (top) plus the corresponding statistical errors (bottom). The map is produced using the numbers of π^- and π^+ tracks in the selected control sample.

is also a detector-induced component due to the difference in the reconstruction efficiencies of $D^+ \to K_s^0\pi^+$ and $D^- \to K_s^0\pi^-$ generated by differences in the track reconstruction and identification efficiencies for π^+ and π^-. While A_{FB} is measured together with A_{CP} using the selected dataset, we correct the dataset itself for the reconstruction and identification effects using control data sets.

In this analysis we have developed a data-driven method to determine the charge asymmetry in track reconstruction as a function of the magnitude of the track momentum and its polar angle. Since B mesons are produced in the process $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ nearly at rest in the CM frame and decay isotropically in the B rest frame, these events provide a very large control sample essentially free of any physics-induced charge asymmetry. However, data recorded at the $\Upsilon(4S)$ resonance also include continuum production $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$), where there is a non-negligible FB asymmetry due to the interference between the single virtual photon process and other production processes, as described above. The continuum contribution is estimated using the off-resonance data rescaled to the same luminosity as the on-resonance data sample. Subtracting the number of reconstrcucted tracks in the rescaled off-resonance sample from the number of tracks in the on-resonance one, we obtain the number of tracks corresponding to the B meson decays only. Therefore, the relative detection and identification efficiencies of the positively and negatively charged particles for given selection criteria can be determined using the numbers of positively and negatively reconstructed tracks directly from data.

Using samples of 8.5 fb^{-1} on-resonance and 9.5 fb^{-1} off-resonance data, applying the same charged pion track selection criteria used in the reconstruction of $D^\pm \to K_S^0\pi^\pm$ decays, and subtracting the off-resonance sample from the on-resonance sample, we obtain a sample of more than 20 million tracks. We use this sample to produce a map for the ratio of detection efficiencies for π^+ and π^- as a function of the track-momentum magnitude and $\cos\theta$, where θ is the polar angle of the track in the laboratory frame. The map and associated statistical errors are shown in Fig. 2. Since the charm meson production is azimuthally uniform, the ϕ dependence of this ratio is found to be very small and uncorrelated with momentum magnitude and polar angle. Therefore, the ratio of detection efficiencies is averaged over the ϕ coordinate. The statistical uncertainties can be reduced by increasing the control sample size, but this would bring a negligible reduction in the final systematic error. In the fit procedure described below, the D^- yields, in intervals of pion-momentum and $\cos\theta$, are weighted with this relative efficiency map to correct for the detection efficiency differences between π^+ and π^-, leaving only FB and CP asymmetries.

Neglecting the second-order terms that contain the product of A_{CP} and A_{FB}, the resulting asymmetry can be expressed simply as the sum of the two. The parameter A_{CP} is independent of kinematic variables, while A_{FB} is an odd function of $\cos\theta_D^*$, where θ_D^* is the polar angle of the $D^\pm$ candidate momentum in the e^+e^- CM frame. If we compute $A(+|\cos\theta_D^*|)$ for the $D^\pm$ candidates in a positive $\cos\theta_D^*$ bin and $A(-|\cos\theta_D^*|)$ for the candidates in its negative counterpart, the contribution to the two asymmetries from A_{CP} is the same, while the contribution from A_{FB} has the same magnitude but opposite sign. Therefore A_{CP} and A_{FB} can be written as a function of $|\cos\theta_D^*|$ as follows:

$$A_{FB}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) - A(-|\cos\theta_D^*|)}{2} \quad (3)$$

and

$$A_{CP}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) + A(-|\cos\theta_D^*|)}{2}. \quad (4)$$

Furthermore, the small fraction of the $D^\pm$ signal yields produced from B meson decays have zero FB asymmetry. As a result, the measured A_{FB} from the $e^+e^- \to c\bar{c}$ production is slightly diluted.

The selected sample is divided into ten subsamples corresponding to ten $\cos\theta_D^*$ bins of equal width and a simultaneous binned ML fit is performed on the invariant mass distributions of D^+ and D^- candidates for each subsample to extract the signal yield asymmetries. The total PDF that describes the distribution is the same as the one used in the fit to the full sample, but some of the parameters (e.g., the signal yields and the asymmetries) can differ between the subsamples. The fit involves a total of 78 free parameters. Using the asymmetry measurements in five positive and in five negative $\cos\theta_D^*$ bins, we obtain five A_{FB} and five A_{CP} values. As A_{CP} does not depend upon $\cos\theta_D^*$, we compute a central value of this parameter using a χ^2 minimization to a constant: $A_{CP} = (-0.39 \pm 0.13)\%$, where the error is statistical only. The A_{CP} and A_{FB} values are shown in Fig. 3, together with the central value and $\pm 1\,\sigma$ confidence interval for A_{CP}.

We perform two tests to validate the analysis procedure. The first involves generating ensembles of toy MC experiments and extracting A_{CP} for each experiment. We determine that the fitted value of the A_{CP} parameter is unbiased, and that the fit returns an accurate estimate of the statistical uncertainty. The second test involves fitting a large number of MC events from the full BABAR detector simulation. We measure A_{CP} from this MC sample to be within $\pm 1\,\sigma$ from the generated value of zero.

The primary sources of systematic uncertainty are the contamination in the composition of particles for the data control sample used to determine the charge asymmetry in track reconstruction efficiencies and statistical uncertainties in the detection efficiency ratios used to weight the D^- yields. The charged pion sample selected to determine the ratio of detection efficiencies for π^- and π^+ contains a contamination of kaons, electrons, muons, and protons at the percent level due to particle misidentification and inefficiencies. This contamination introduces a small bias in the A_{CP} measurement due to the slightly different particle identification efficiencies between positively and negatively charged non-pion particles. The

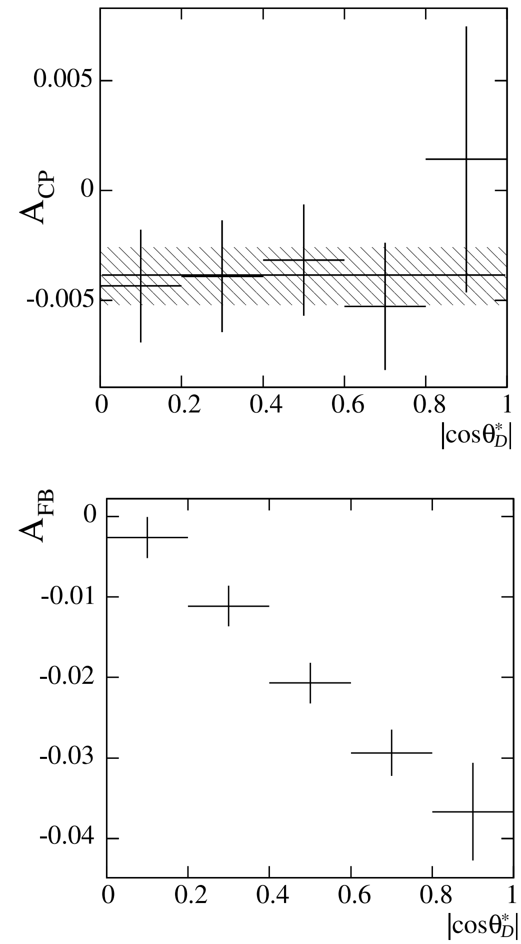

FIG. 3: A_{CP} (top) and A_{FB} (bottom) asymmetries for $D^\pm \to K_S^0\pi^\pm$ candidates as a function of $|\cos\theta_D^*|$ in the data sample. The solid line represents the central value of A_{CP} and the hatched region is the $\pm 1\,\sigma$ interval, both obtained from a χ^2 minimization assuming no dependence on $|\cos\theta_D^*|$.

particle identification efficiencies are separately measured in the data for positively and negatively charged tracks. They are found to be in a good agreement with the MC simulation. We therefore study this bias using the MC simulated events and determine the bias to be $+0.05\,\%$. As a result, we shift the measured A_{CP} by $-0.05\,\%$ to correct for the bias and then, conservatively, include the same value as a contribution to the systematic uncertainty. Therefore the bias-corrected value of A_{CP} is $(-0.44 \pm 0.13)\%$.

The technique used here to remove the charge asymmetry from detector-induced effects produces a small systematic uncertainty in the measurement of A_{CP} due to the statistical error in the relative efficiency map ($\pm 0.06\%$). Using MC simulation, we evaluate an additional systematic uncertainty of $\pm 0.01\%$ due to a possible charge asymmetry present in the control sample before applying the selection criteria. Combining these two contributions with the systematic contribution from the difference in the composition of the control sample compared to the signal sample ($\pm 0.05\%$), as described earlier, the total contribution from the correction technique is $\pm 0.08\%$, which is the dominant source of systematic error. We also consider a possible systematic uncertainty due to the regeneration of K^0 and $\overline{K}^0$ mesons in the material of the detector. K^0 and $\overline{K}^0$ mesons produced in the decay process can interact with the material around the interaction point before they decay. Following a method similar to that described in [11], we compute the probability for K^0 and $\overline{K}^0$ to interact inside the *BABAR* tracking system. We numerically integrate the interaction probability distribution, which depends on the measured nuclear cross-section for $K^{\pm}$ (assuming isospin symmetry), the amount of material in the *BABAR* beam-pipe and tracking detectors, the $K^0/\overline{K}^0$ time evolutions, and the K^0_S kinematic distribution and reconstruction efficiency as determined from simulation studies. From the difference between the interaction probabilities for K^0 and $\overline{K}^0$, we estimate a systematic uncertainty of $\pm 0.06\%$. Minor systematic uncertainties from the simultaneous ML fit are also considered: the choice of the signal and background PDF, the limited data set in the MC signal sample, and the choice of binning in $\cos\theta^*_D$, for a total contribution of $\pm 0.01\%$. The combined systematic uncertainty in the CP asymmetry measurement including all the contributions is calculated as the quadrature sum and is found to be $\pm 0.10\%$.

In conclusion, we measure the direct CP asymmetry, A_{CP}, in the $D^{\pm} \to K^0_S \pi^{\pm}$ decay using approximately 800,000 $D^{\pm}$ signal candidates. We obtain

$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\,\%, \tag{5}$$

where the first error is statistical and the second is systematic. The result is consistent with the prediction of $(-0.332 \pm 0.006)\%$ for this mode based on the SM.

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